First results from BNL E949 on $K^+ \to$ ð$^+$íí̄

For the E949 collaboration:

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Stony Brook Physics Department HEP seminar

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Outline

- Theoretical motivation
    - CKM matrix
    - The decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- The E949 experiment:
    - Aparatus & measurement
    - Past (E787) results
    - Analysis strategy
- The result

CKM matrix

The CKM matrix relates weak with strong eigenstates. In the Wolfenstein parametrization (to O($ë^7$)),

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{l^2}{2} & l & Al^3(r-ih) \\ -l & 1-\frac{l^2}{2} & Al^2 \\ Al^3(1-\bar{r}-i\bar{h}) & -Al^2 & 1 \end{pmatrix}$$

where $\bar{r} = r\left(1-\frac{l^2}{2}\right)$, $\bar{h} = h\left(1-\frac{l^2}{2}\right)$

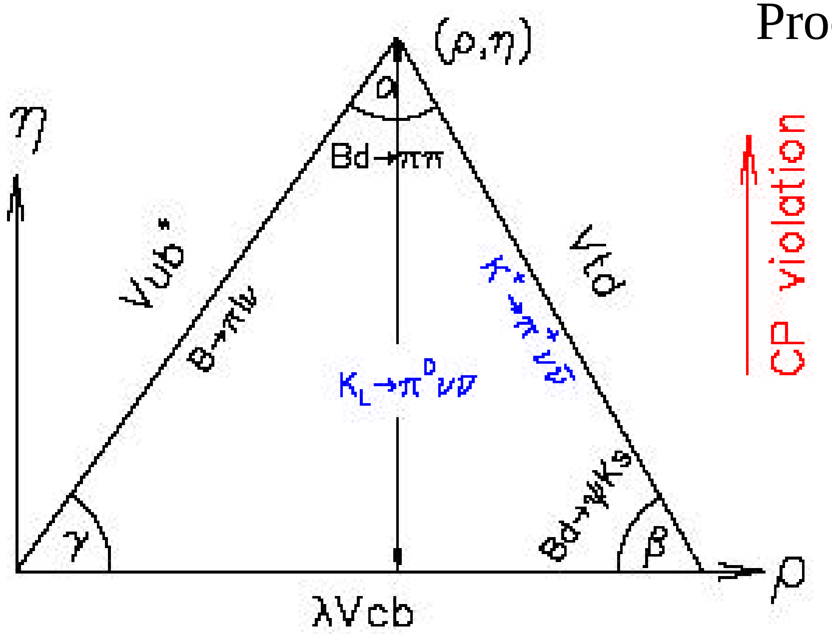
CP violation arises from the irreducible imaginary phase of V_{CKM} , because it's 3x3 (3 generations)

Unitarity triangle

V_{CKM} is unitary, i.e. $VV^{+}=I \Rightarrow$ 6 relations of $V_{ij} = 0$

For example, $V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$

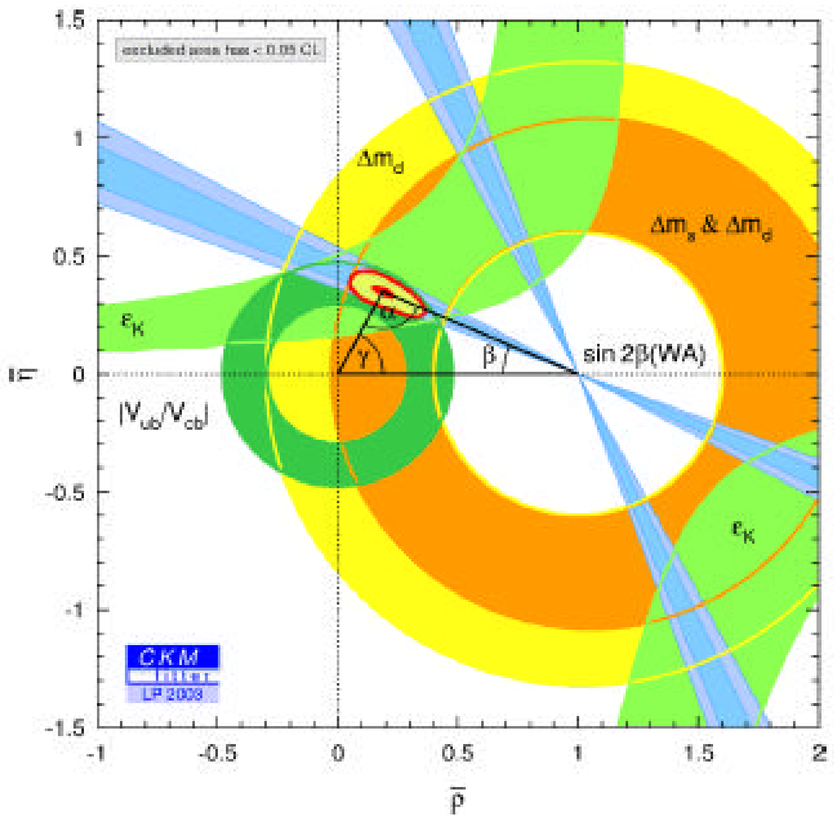
$\Rightarrow$A "Unitarity triangle" in the ñ-ç plane ($V_{ud} \cong 1$, $V_{tb}= 1$) :



Processes w/ small theoretical uncertainties:

Process	Experiments
$\mathcal{B}(\mathrm{K}^{+} \to \pi^{+}\nu\bar{\nu})$	E787/E949, FNAL-E921
$\mathcal{B}(\mathrm{K}^{0}_{\mathrm{L}} \to \pi^{0}\nu\bar{\nu})$	KOPIO, E391a
$\mathcal{A}(B \to J/\psi \mathrm{K}^{0}_{\mathrm{S}})$	BaBar, Belle
CP violating decay rate asymmetry	
$\Delta M_{B_s}/\Delta M_{B_d}$	CDF, D0, LHCb, BTeV
ratio of mixing frequencies of B_s and B_d mesons	

Measurements of unitarity triangle



$|V_{ub}|$, $|V_{cb}|$: tree-level semileptonic B decays

$|V_{td}|$: $\ddot{A}M_{Bs}$/ $\ddot{A}M_{Bd}$ & $K^{+}\rightarrow$ ð$^{+}$íī

sin2â (& 2á) : CP assymetry in hadronic B decays

A($B_d \rightarrow$ J/ø $\hat{E}_s{}^{o}$) &

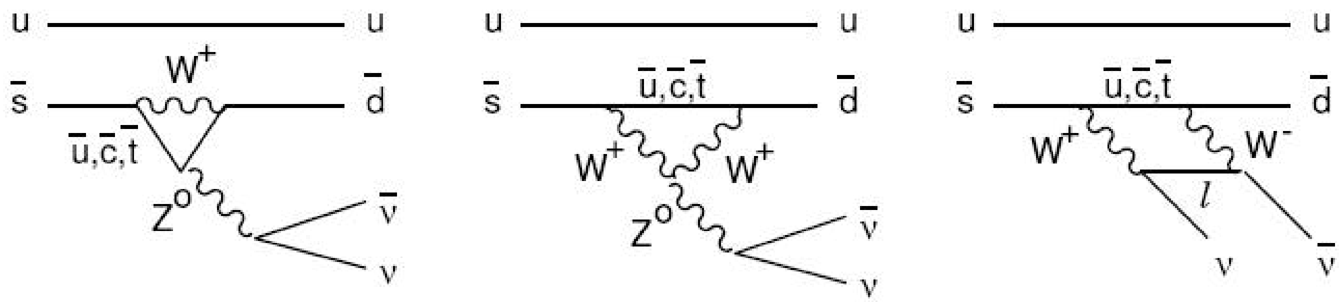
BR($K^{+}\rightarrow$ð$^{+}$íī)/BR($K^{ï}\rightarrow$ ð^{ï}íī)

$å_{ê}$ comes from CP violation in the K sector

A better determination of V_{td} from $K^{+}\rightarrow$ ð$^{+}$íī will provide a sensitive test of the SM by comparing the results from the K and B sector and probe new physics

The SM K^+® ð$^+$íí̄ BR

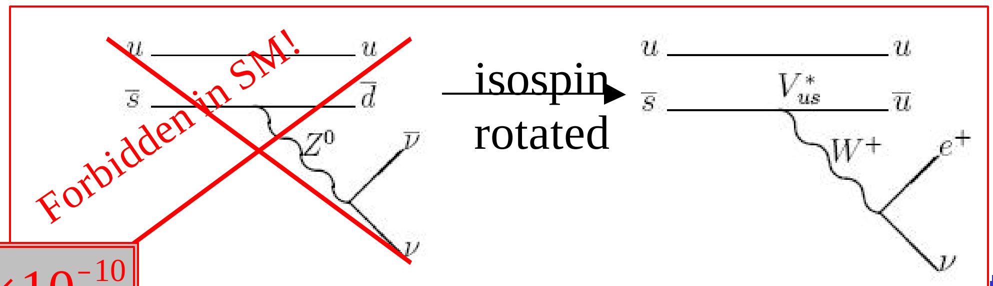
- All processes at 2nd order
- Main contribution of t in the loop (u & c cancel by GIM mechanism)
- Very theoretically “clean” calculation (precision < 5%, uncertainties mainly from c sector)



$$BR(K^+ \to p^+ n\bar{n}) \propto \sum_{l=e,m,t} \left| \left[\overbrace{V^*_{cs}V_{cd}}^{\text{ë}_c} X(c_c) + \overbrace{V^*_{ts}V_{td}}^{\text{ë}_t} X(c_t) \right] \times \underbrace{(HADR)} \times (\bar{n}_l n_l) \right|^2 \Rightarrow$$

$$\ldots BR \propto (s\bar{h})^2 + (r_o - \bar{r})^2$$ $\longrightarrow$ **ellipse in ñ-ç plane**

$$s = \left(\frac{1}{1 - l^2/2} \right)^2$$

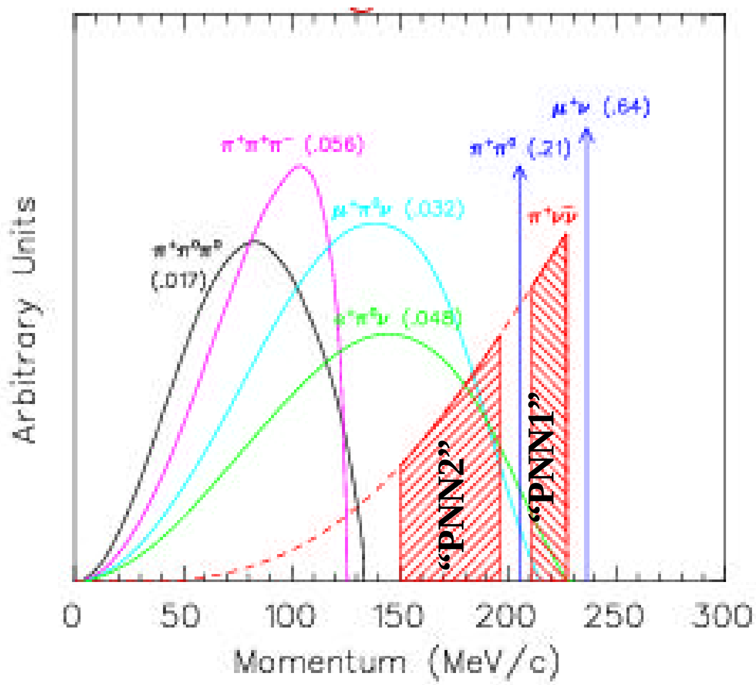


$$BR_{th}(K^+ \to p^+ n\bar{n}) = (0.77 \pm 0.11) \times 10^{-10}$$

The measurement, backgrounds

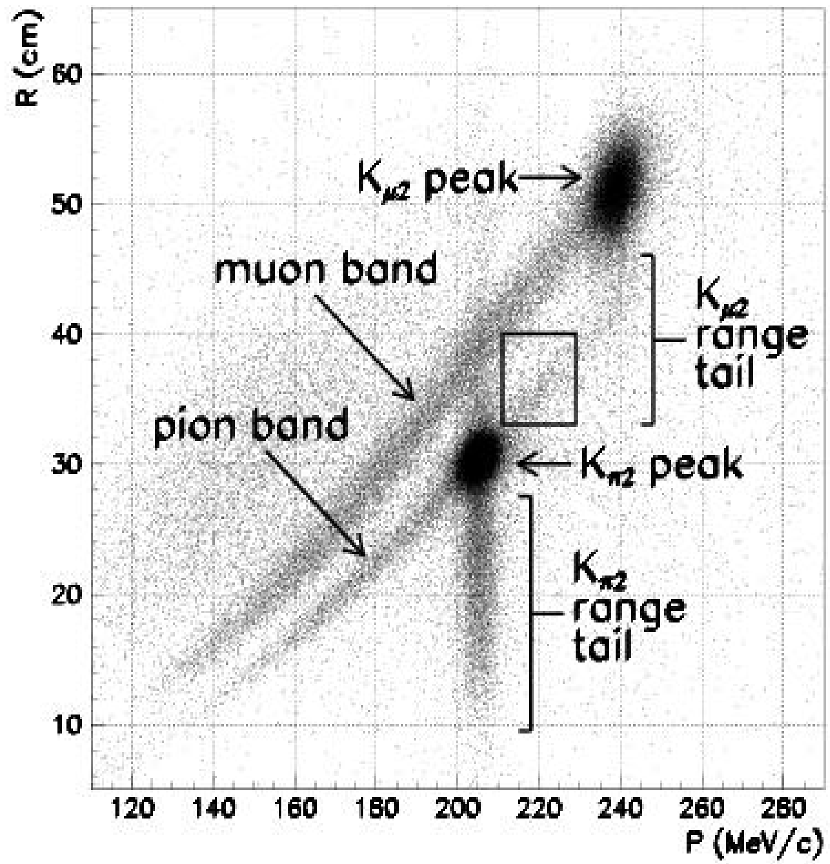
- 3-body decay w/ 2 missing particles: $0 \leq p_{ð+} \leq 227$ MeV/c $\Rightarrow$

  Signal: ð$^{+}$ + nothing , backgrounds vetoed ~ 10^{-11} !
- Need
  - particle identification (PID)
  - all other charged particles vetoed < 10^{-3}
  - redundant precise kinematic measurements



Decay	$\mathcal{B}$	PID	veto	kine.
$K^+ \to \pi^+\pi^0$	0.21	-	$\surd\ \surd$	$\surd$
$K^+ \to \mu^+\nu$	0.63	$\surd$	-	$\surd$
$K^+ \to \mu^+\nu\gamma$	0.005	$\surd$	$\surd$	-
$K^+ \to \pi^0\mu^+\nu$	0.032	$\surd$	$\surd\ \surd$	-
$K^+ \to \pi^0 e^+\nu$	0.048	$\surd$	$\surd\ \surd$	-
$K^+ \to \pi^+\pi^-\pi^+$	0.056	-	$\surd$	$\surd\ \surd$

More on backgrounds



Decay product (ð$^+$ or ì$^+$) range in scintillator vs momentum:

- 2-body decay peaks
- 3-body decay bands
- scaterring tails

The E949 collaboration

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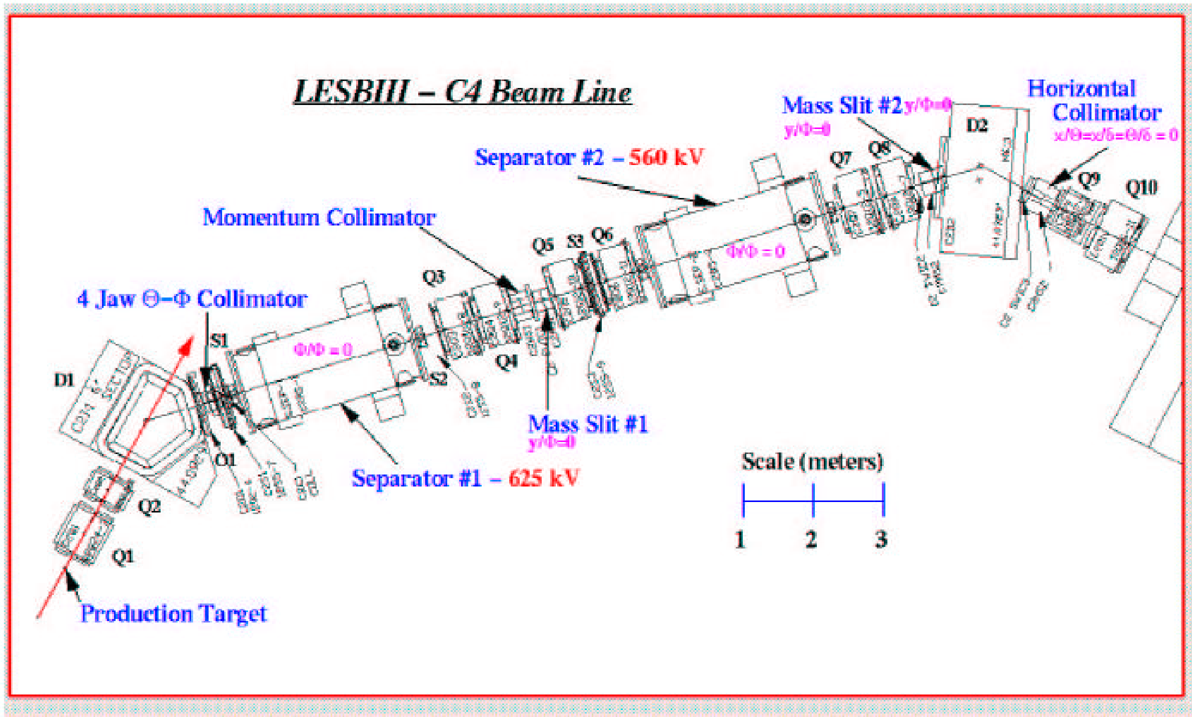
Students and post-docs in red.

~70 physicists, plus a lot of hard work from earlier E787 collaborators.

The beam

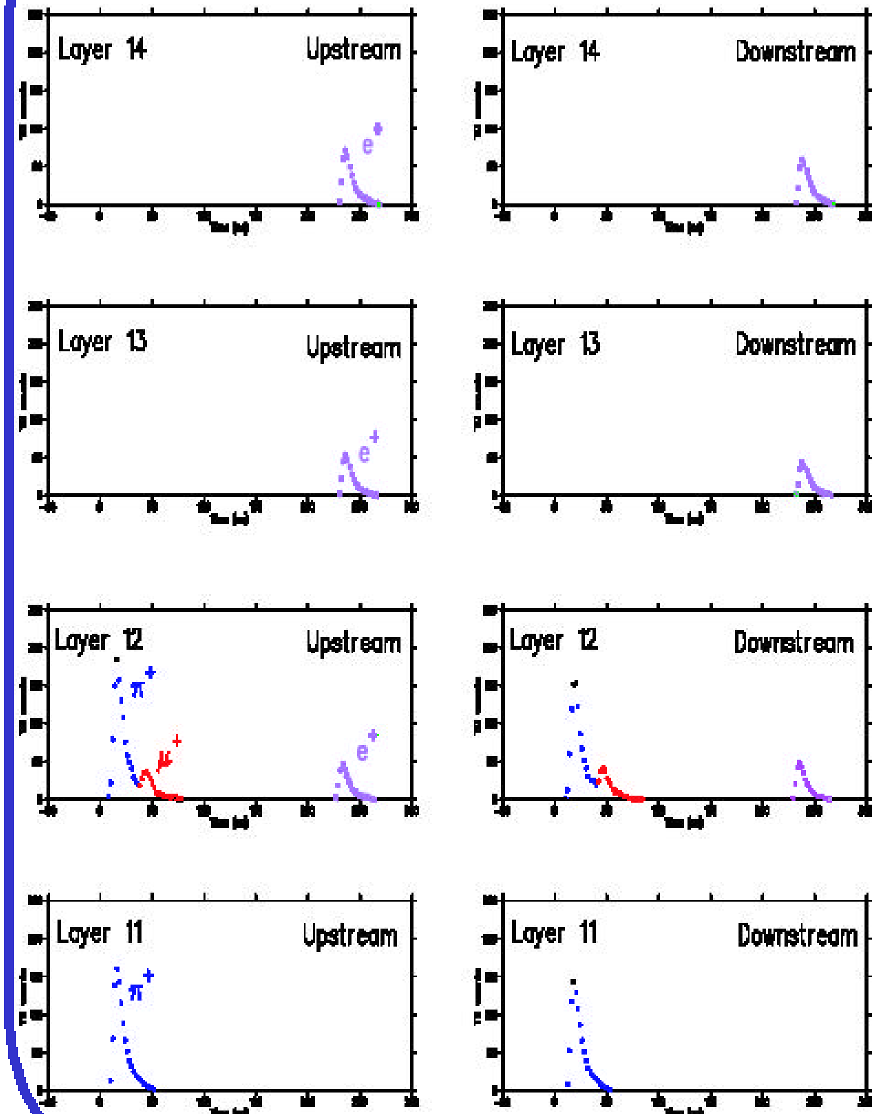


• The AGS extracts ~ 65×10^{12} protons at 22 GeV/c momentum over a 2.2 sec spill, every 5.4 sec.

• They are shot on platinum target and particles produced ~ 0^{o} are sent to the Low Energy Separated Beamline (LESB III), where K^{+} are electrostatically separated from ð$^{+}$ and focused

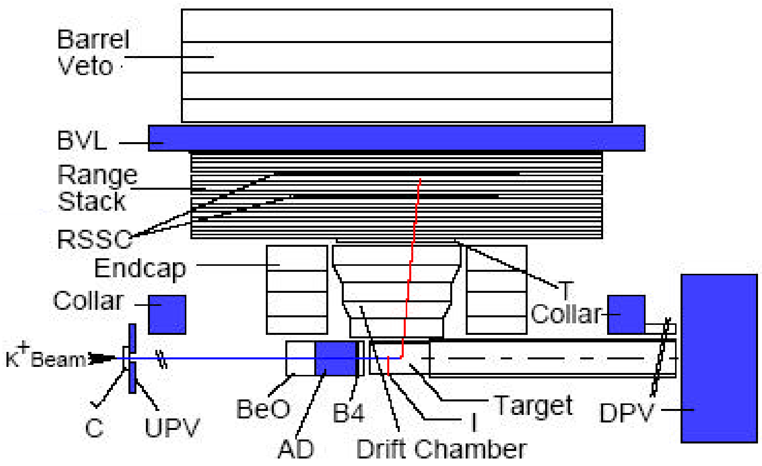
• Finally in the E949 target, ~ 3.5×10^{6} K^{+}/spill arrive and stop, with a ratio of K/ð ~ 2.5-3

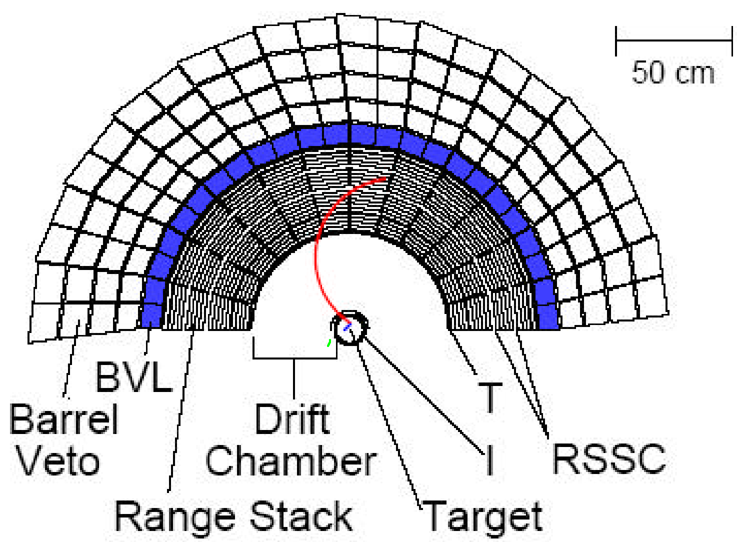
The measurement w/ E949 detector



- Incoming 700MeV/c beam K^+: identified by ckov, WC, scint. hodoscope (B4). Slowed down by BeO and AD
- K^+ stops & decays at rest in scintillating fiber target – measure delay (2ns)
- Outgoing ð$^+$: verified by IC, VC, T counter. Momentum measured in UTC, energy & range in RS and target (1T magnetic field parallel to beam)
- ð$^+$ stops & decays in RS – detect ð$^+$→ì$^+$→e^+ chain
- Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV

The measurement w/ E949 detector





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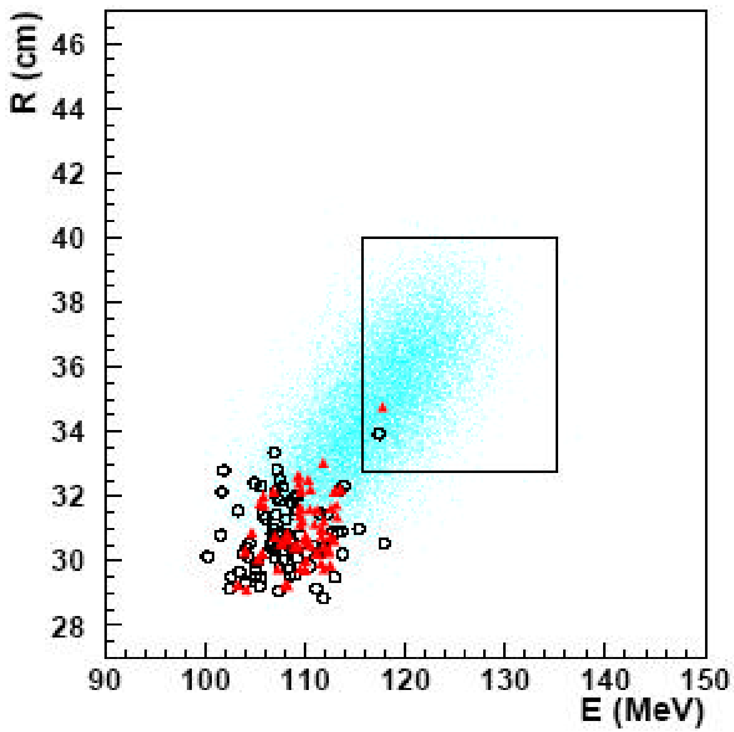
(1T magnetic field parallel to beam)

- ð$^+$ stops & decays in RS – detect ð$^+$→ì$^+$→e$^+$ chain
- Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV
- New/upgraded elements

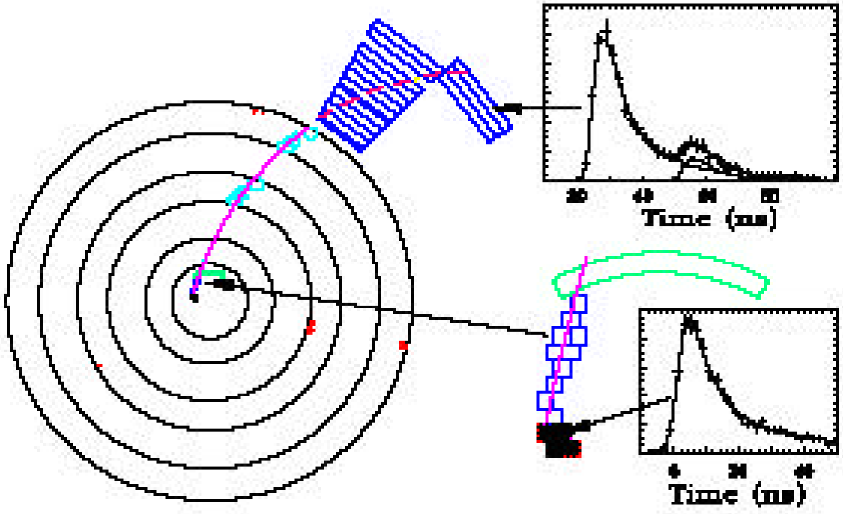
Previous (E787) results (1)

	PNN1	PNN2
Pð (MeV/c)	[211,229]	[140,195]
Years	1995-98	1996-97
Stopped K⁺	5.9×10^{12}	1.7×10^{12}
Candidates	2	1
Background	0.15±0.05	1.22±0.24
BR(K⁺® ð⁺íí)	$(1.57^{+1.75}_{-0.82})\times10^{-10}$	$< 22\times10^{-10}$ (90% CL)

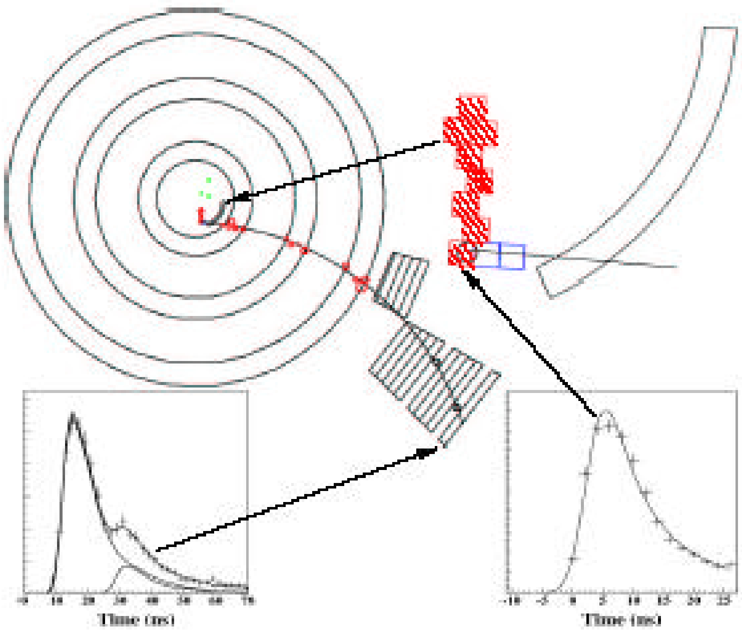


Previous (E787) results (2)

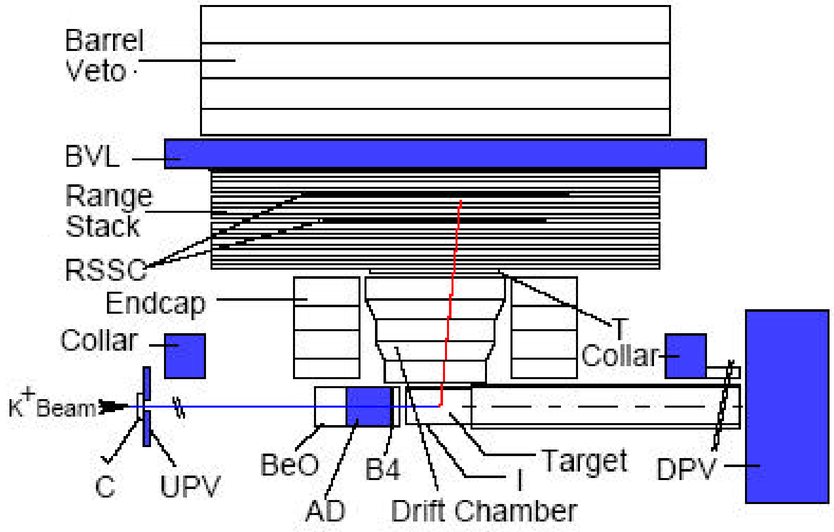
Candidate E787A

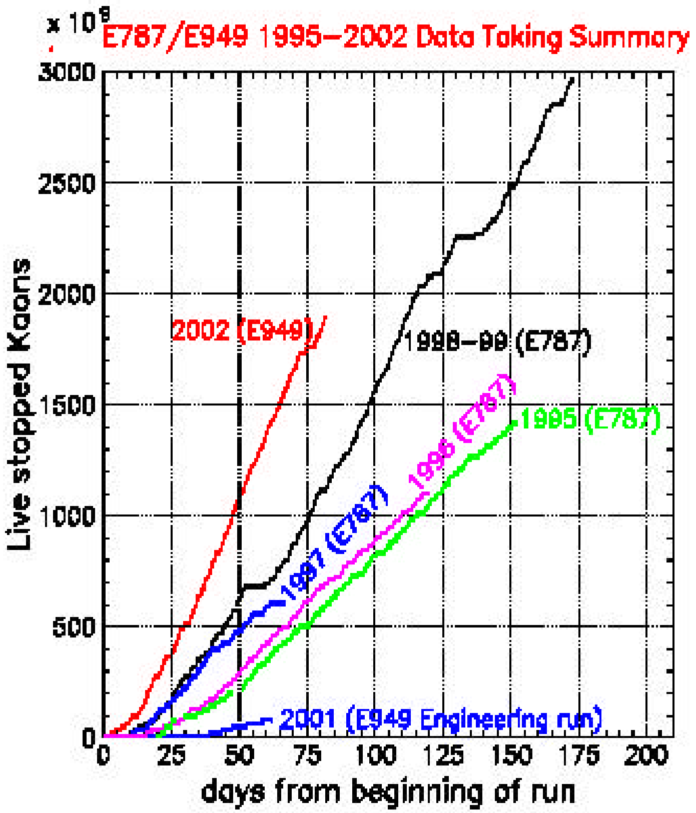


Candidate E787C



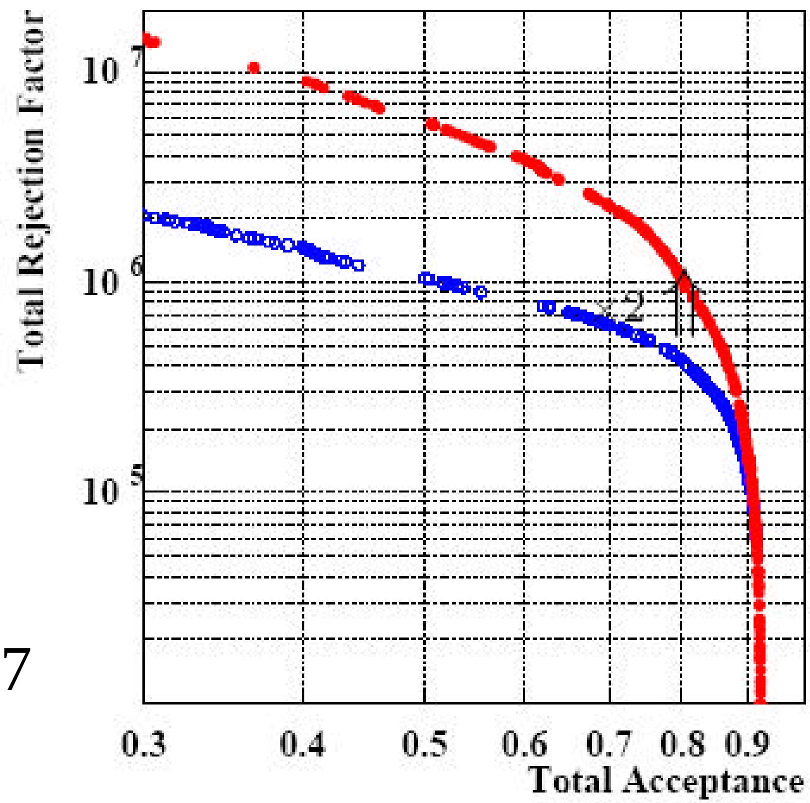
What's new in E949?





- New/upgraded PV elements
- More protons from AGS
- Improved tracking and energy resolution
- Higher rate capability due to DAQ, electronics and trigger improvements
- Lower beam duty factor (spill time/ time between spills)
- Lower proton energy
- Problematic separators, worse K/ð ratio

Photon Veto improvement



~ 2 × better rejection at nominal PNN1 acceptance (80%) or

~ 5% more acceptance with E787 rejection !

* Good news for PNN2 as well…

E787, E949

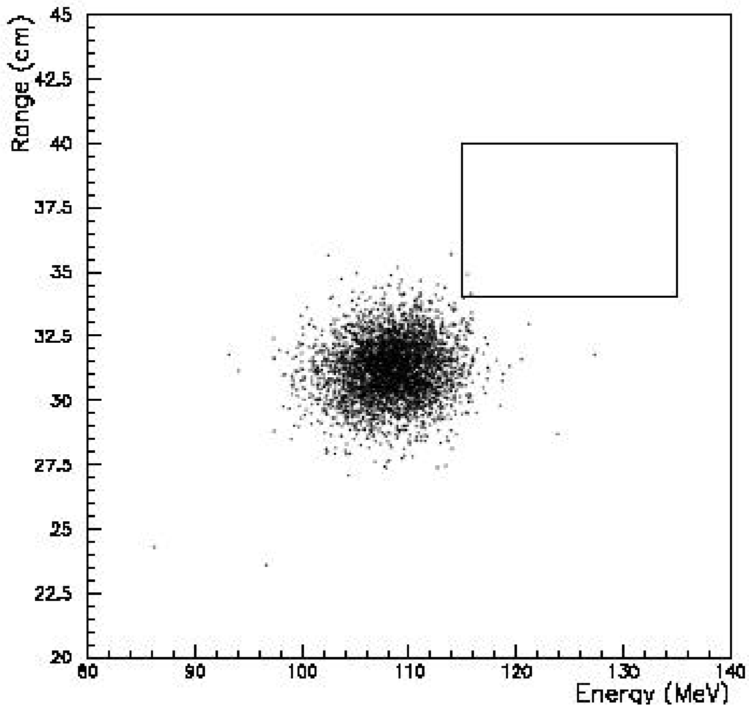
Analysis strategy (1)

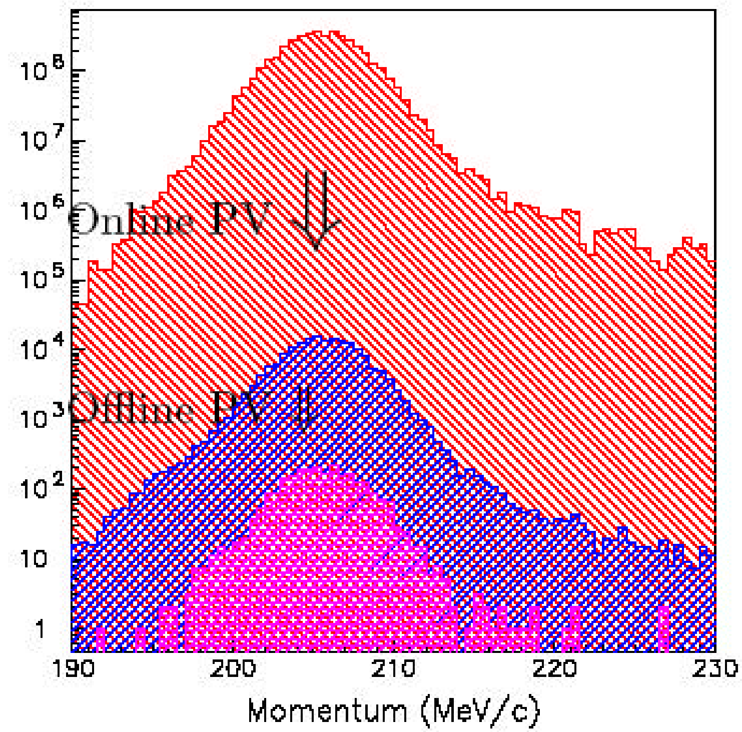
- "Blind" analysis: don't examine signal region ("the box") until all bg are verified
- A priori identification of bg sources
- To avoid bias, tune cuts using *randomly selected* 1/3 of the data, then measure bg with remaining 2/3
- Suppress each bg source w/ at least two independent cuts
- Bg cannot be reliably simulated ⇒ measure w/ data by inverting cuts and measuring rejection

Source	Suppresion method			
	Kinematics	Particle ID	Veto	Timing
$K^+ \to \mu^+\nu(\gamma)$ ($K_{\mu 2}$)	√	√	(√)	
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	√		√	
Scattered π^+ beam		√		√
CEX			√	√

$\mathrm{CEX} \equiv K^+ n \to K^0 p\ ,\ K^0_L \to \pi^+ \ell^- \nu$

Example: K^{+}® ð$^{+}$ð^{ï} bg rejection





Select events with photons, measure rejection of kinematic cuts (P, R, E "box")

Select $K^{+}\rightarrow$ð$^{+}$ð^{ï} kinematically, measure rejection of photon veto

Analysis strategy (2)

• Verify bg estimates & check for correlations by *simultaneously* loosening both cuts and comparing observed and predicted number of events remaining.

• Construct background functions by varying *one cut at a time*, keeping the other inverted. Use them to estimate bg in the box.

• Use MC to measure geometrical acceptance, verify by measuring BR($K^+\rightarrow ð^+ð^{ï}$)

Expected bg

	PV×KIN	10×10	20×20	20×50	50×50	50×100
$K_{\pi 2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD×KIN	10×10	20×20	50×50	80×50	120×50
$K_{\mu 2}$	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD×KIN	10×10	20×20	50×20	80×20	80×40
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

K$_{\text{ìm}}$ :: 3-body decays w/ muons (K⁺→ì⁺íã, Ê⁺→ðïì⁺í) and Ê⁺→ð⁺ðï, ð⁺→ì⁺í

TD :: ð→ì→e identification

PV :: Photon Veto

KIN :: kinematic cuts

M×N :: reduction in rejection w.r.t. predefined 1×1 region by loosening the cuts - ***same increase in bg expected***

Quantify consistency: Fit $N_{\text{obs}} = cN_{\text{pred}}$ and expect $c = 1$.

Background	c	χ^2 Probability	Total background
$K_{\pi 2}$	$0.85^{+0.12}_{-0.11}$	0.17	0.216 ± 0.023
$K_{\mu 2}$	$1.15^{+0.25}_{-0.21}$	0.67	0.044 ± 0.005
$K_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40	0.024 ± 0.010

Beam & CEX: 0.014 ± 0.003

Total bg in signal region:
0.30 ± 0.03

E949 improved analysis strategy

- E787 bg estimation methods are reliable $\Rightarrow$ confident to increase signal region by loosening cuts to gain acceptance, at cost of more total bg
- Divide signal region into cells, calculate expected bg (b_i) and signal (s_i) for each cell using the background functions
- Calculate BR using s_i/b_i of cells where event(s) are found, using likelihood ratio method:

Maximize $\quad X = \prod_{i=1}^{n} X_i \quad , \quad X_i = \dfrac{\dfrac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!}}{\dfrac{e^{-b_i} b_i^{d_i}}{d_i!}}$

where d_i the number of candidates in cell i

n the total number of cells

Likelihood ratio method

To calculate confidence levels:

- Poisson probability for sg+bg and for bg only:

$$P_{s+b} = \prod_{i=1}^{n} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i\,!}$$

$$P_b = \prod_{i=1}^{n} \frac{e^{-b_i} b_i^{d_i}}{d_i\,!}$$

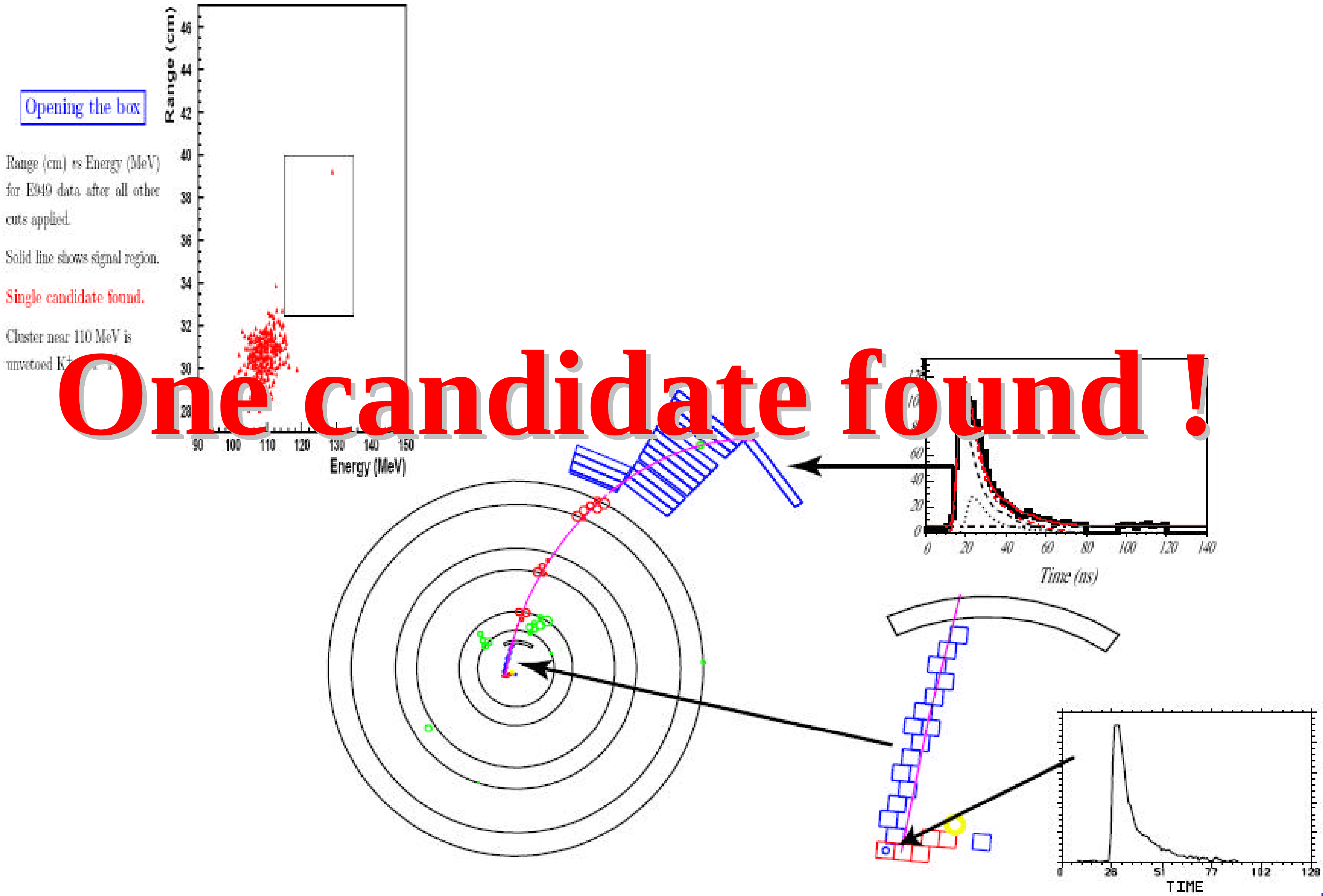
- Sum over all configurations that give $X \le X_{\text{observed}}$ (less "signal-like"):

$$CL_{s+b} = P_{s+b}(X \le X_{obs}) = \sum_{X(\{d_i\}) \le X(\{d_{i,obs}\})} P_{s+b}$$

$$CL_b = P_b(X \le X_{obs}) = \sum_{X(\{d_i\}) \le X(\{d_{i,obs}\})} P_b$$

- *Modified Frequentist confidence level*: $CL_s = \dfrac{CL_{s+b}}{CL_b}$

Opening the box



One candidate found !

First E949 results
Ilektra A. Christidi

Evaluation of the candidate

How likely is it that the candidate is due to known background?

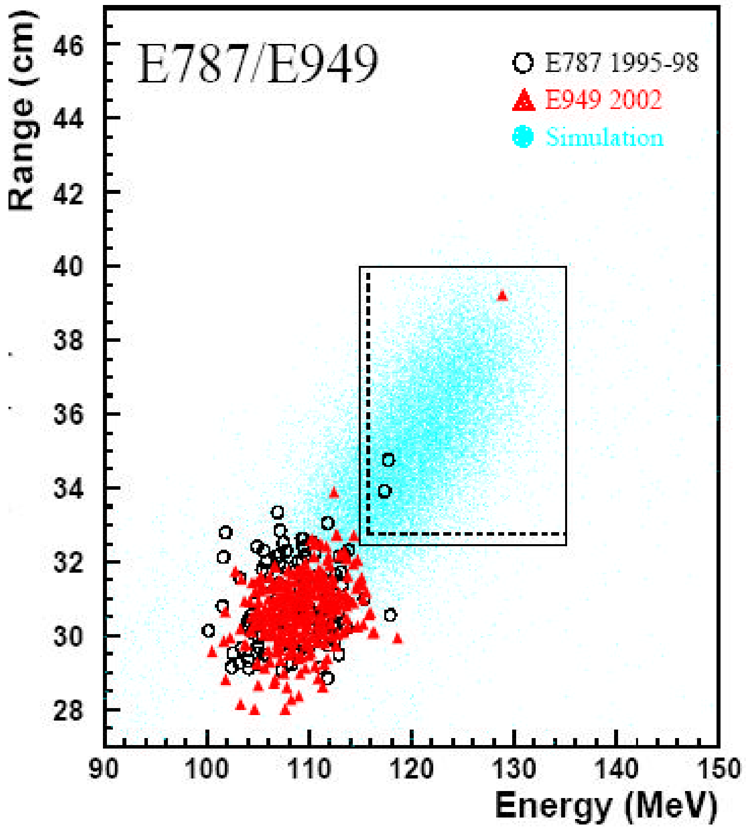
- If there are 100 identical experiments, then 7 of them will have a candidate from a known bg source, that is as signal-like or more than our candidate.

- The sum of expected bg events in all cells with $s_i/b_i \geq$ to the one the event was found, is 0.077. The probability that they could produce one or more events is 0.074 (~ 7/100) ≡ $1\text{-}CL_b$

The E949 candidate is more likely to be due to bg ("dirtier") than the E787 candidates…

Candidate	E787A	E787C	E949A
Probability	0.006	0.02	0.07

Combined result



$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$$

(68% CL interval)

E787 result:

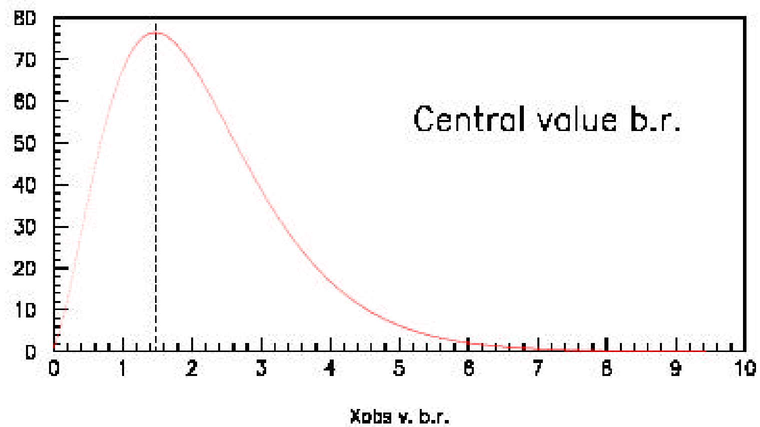
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$$

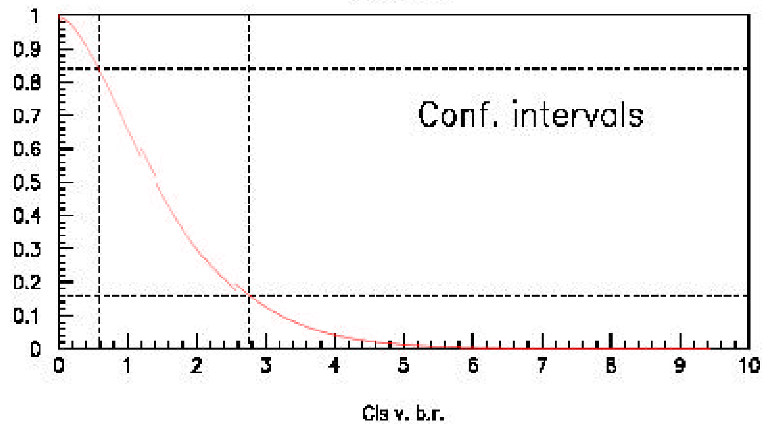
	E787		E949
Stopped K$^+$ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}		2.6×10^{-10}
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i+b_i}$	0.98	0.88	0.48

Some more details…

$$\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\overline{\nu}) > 0.42 \times 10^{-10} \text{ at } 90\% \text{ CL.}$$
$$\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\overline{\nu}) < 3.22 \times 10^{-10} \text{ at } 90\% \text{ CL.}$$

$0.0055 < |V_{td}| < 0.0271$





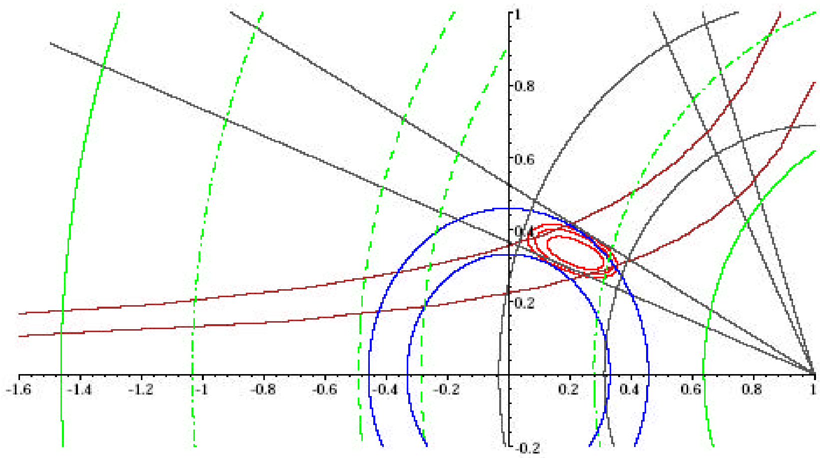
✓ The probability that known bg sources give a configuration of 3 events as signal-like as the 2 E787 + 1 E949 events or more, is *0.001*

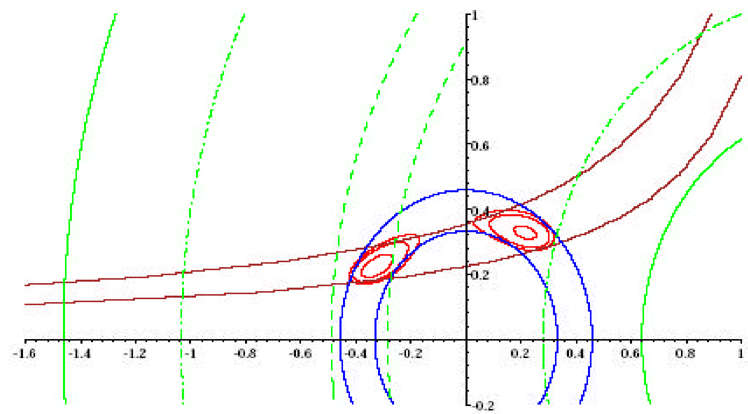
(compare to 0.077 for E949 alone)

? Central value, although smaller, is still ~ 2 × SM , but consistent within errors…

Effect on unitarity triangle

Thanks to Gino Isidori





Without constraints that depend on B_d mixing

Limits from measurements of:

BR(K^+ - ð$^+$íí) : ------- central value

- · - · · 68% interval

—— 90% interval

$å_{Ê}$

$|V_{ub}|/|V_{cb}|$

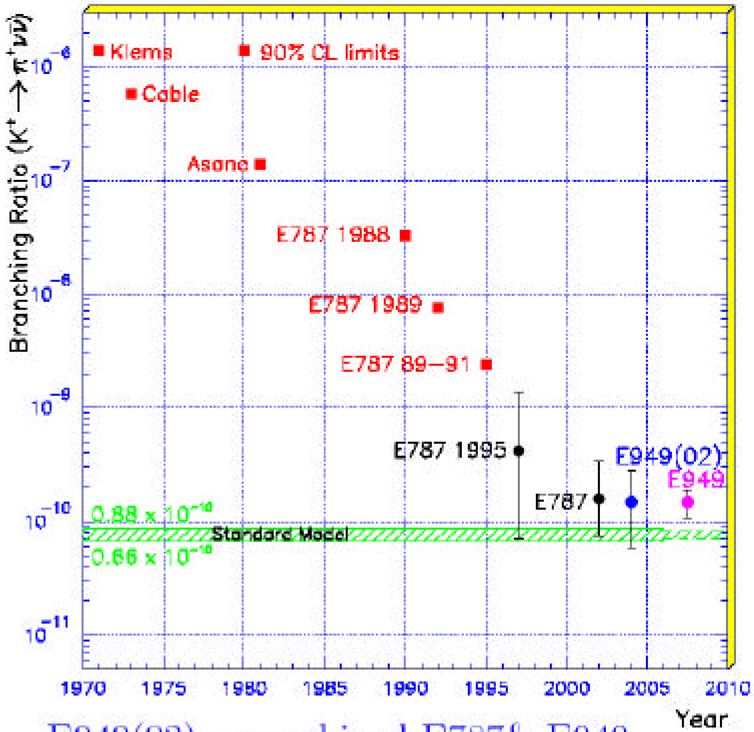
sin2â

Ä $Ì_d$, Ä $Ì_s$ /Ä $Ì_d$

} Depend on B_d mixing

Combined all but K^+ - ð$^+$íí (68%, 90%, 95%)

Progress & future prospects



E949(02) = combined E787& E949.

E949 projection with full running period.

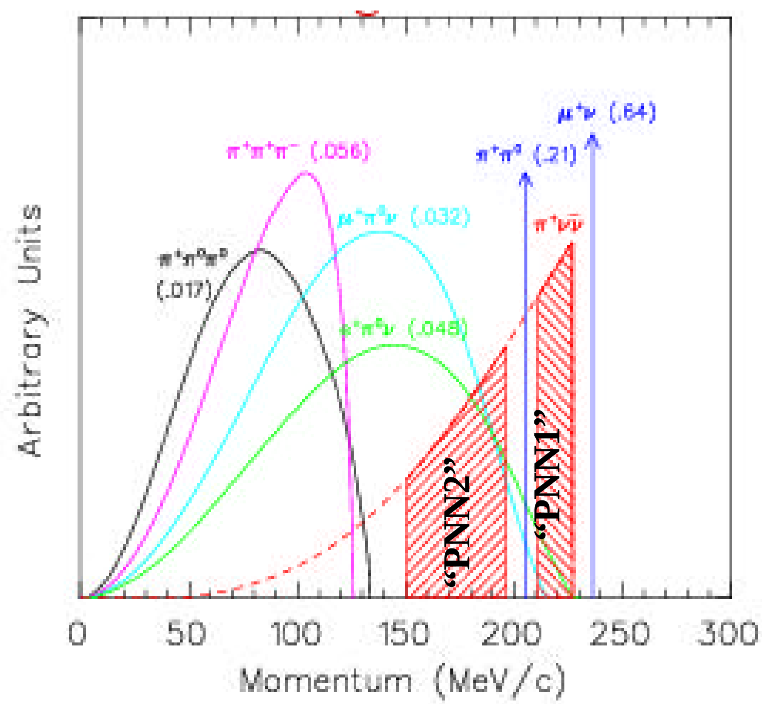
✓ *Obviously, more statistics are needed! ® more E949 running would be desirable*

✓ Analysis on PNN2 data (phase space below the K^{+}→ð$^{+}$ð^{ï} peak) currently in progress

Narrowing of SM prediction assumes better measurement of B_s mixing consistent w/ SM

PNN2 analysis (1)

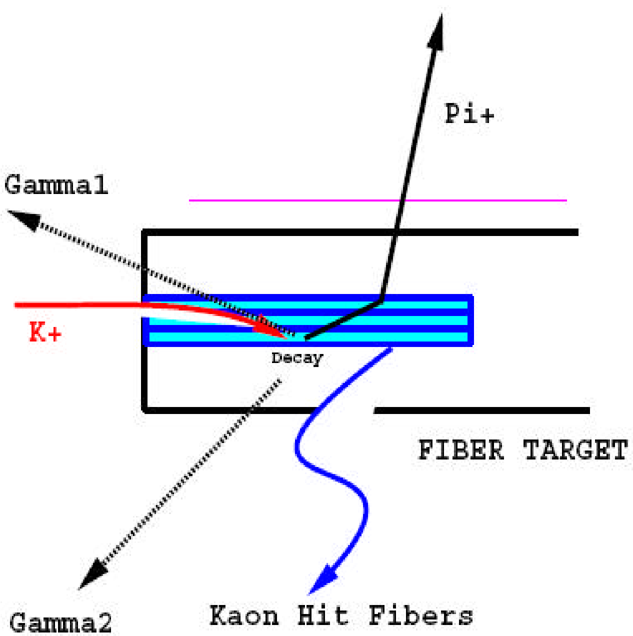
- More phase space than PNN1
- Probes different part of P_{π} spectrum → enhance validity of PNN1 result
- More background, scales the same as signal

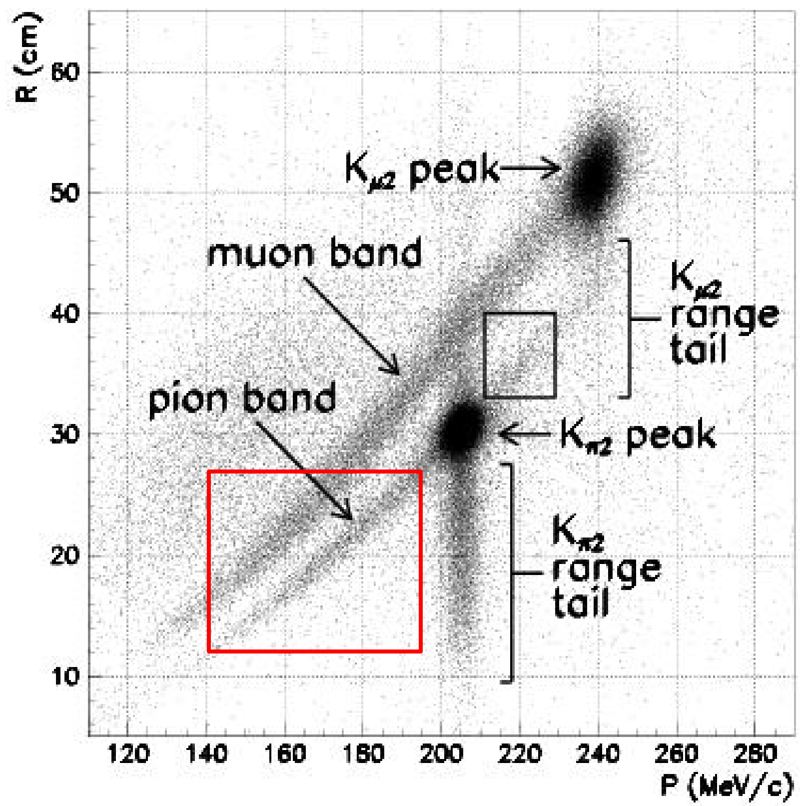


PNN2 analysis (2)

Main bg mechanism: K$^+$→ð$^+$ð^{ï} with ð$^+$ scatter in target ⇒

- Simultaneous shift in range AND momentum
- Photons head near beam direction, the weakest PV region of the detector





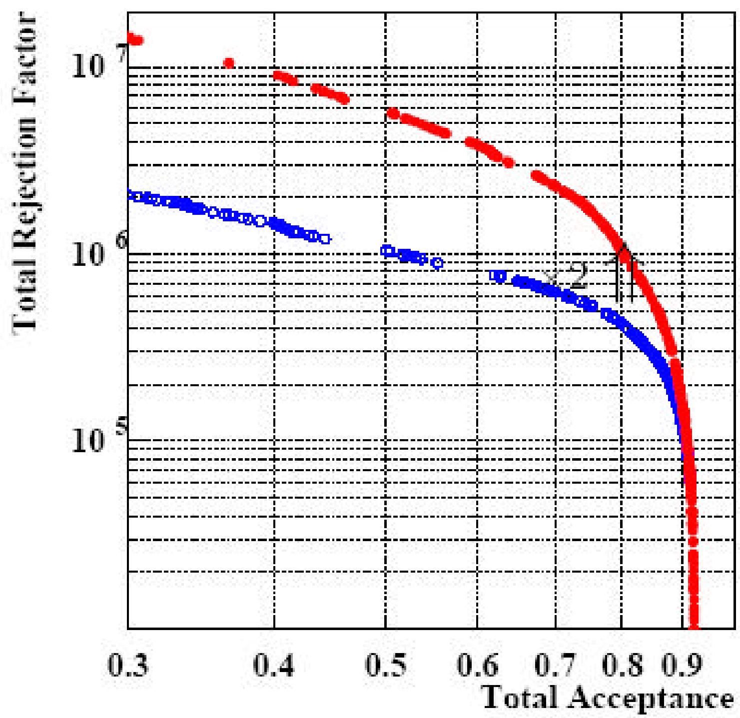
PNN2 analysis (3)

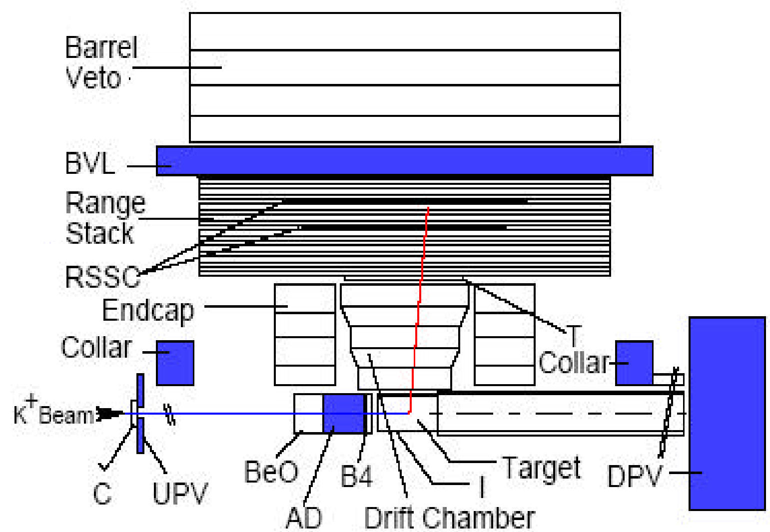
- *Goal: sensitivity equal to PNN1, s/b = 1* $\Rightarrow$

  $2 \times$ acceptance and $5 \times$ rejection

- Improved PV: new detectors at small angles

- Improved algorithms to identify ð$^+$ scatters in target





Conclusions

- E787 upgrade into E949 worked as expected

- One $K^+ \to p^+ n\bar{n}$ candidate event observed, bringing the BR to $BR(K^+ \to p^+ n\bar{n}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$, which is still consistent with the SM

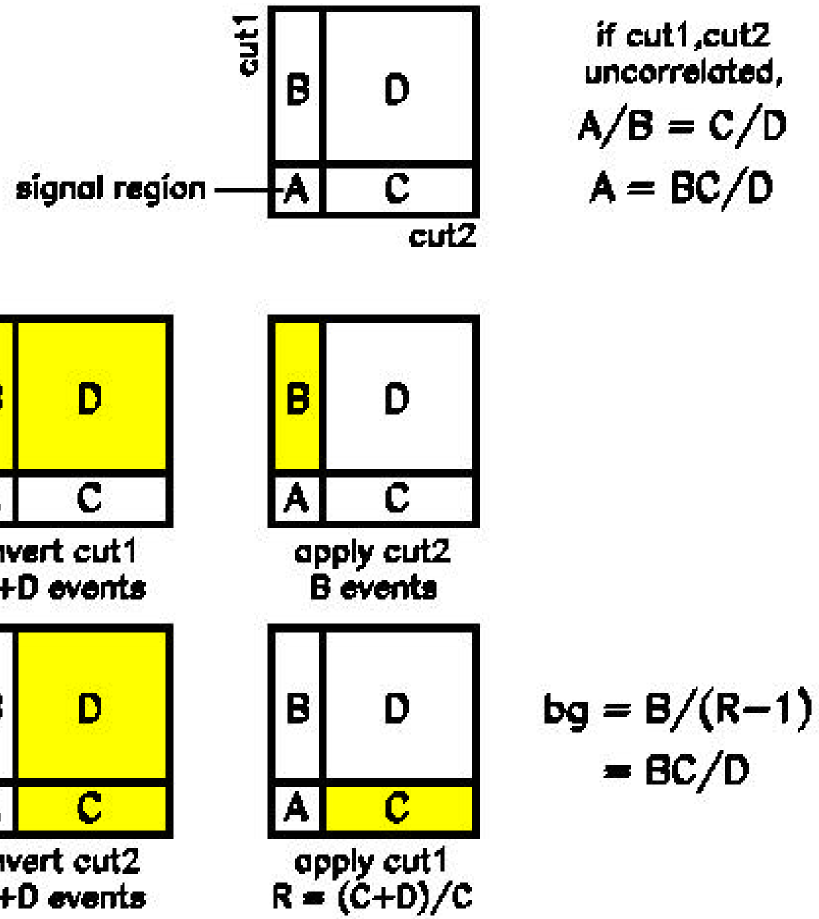
- Additional running needed for more influencial results

- PNN2 analysis is under way

Extras

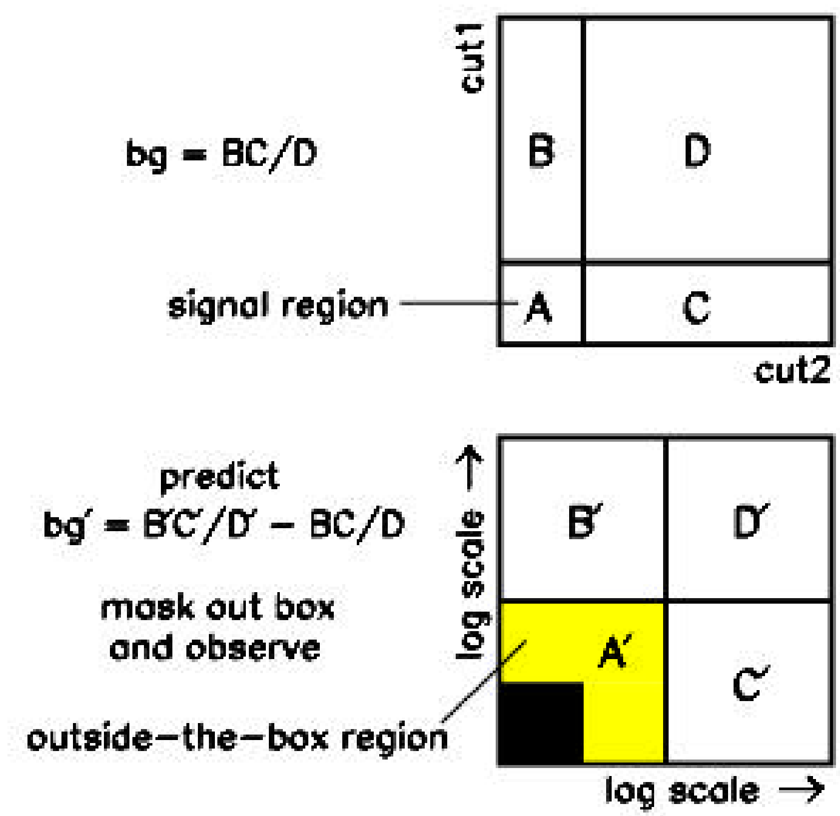
Analysis strategy (2)

• Bg cannot be reliably simulated ⇒ measure w/ data by inverting cuts and measuring rejection

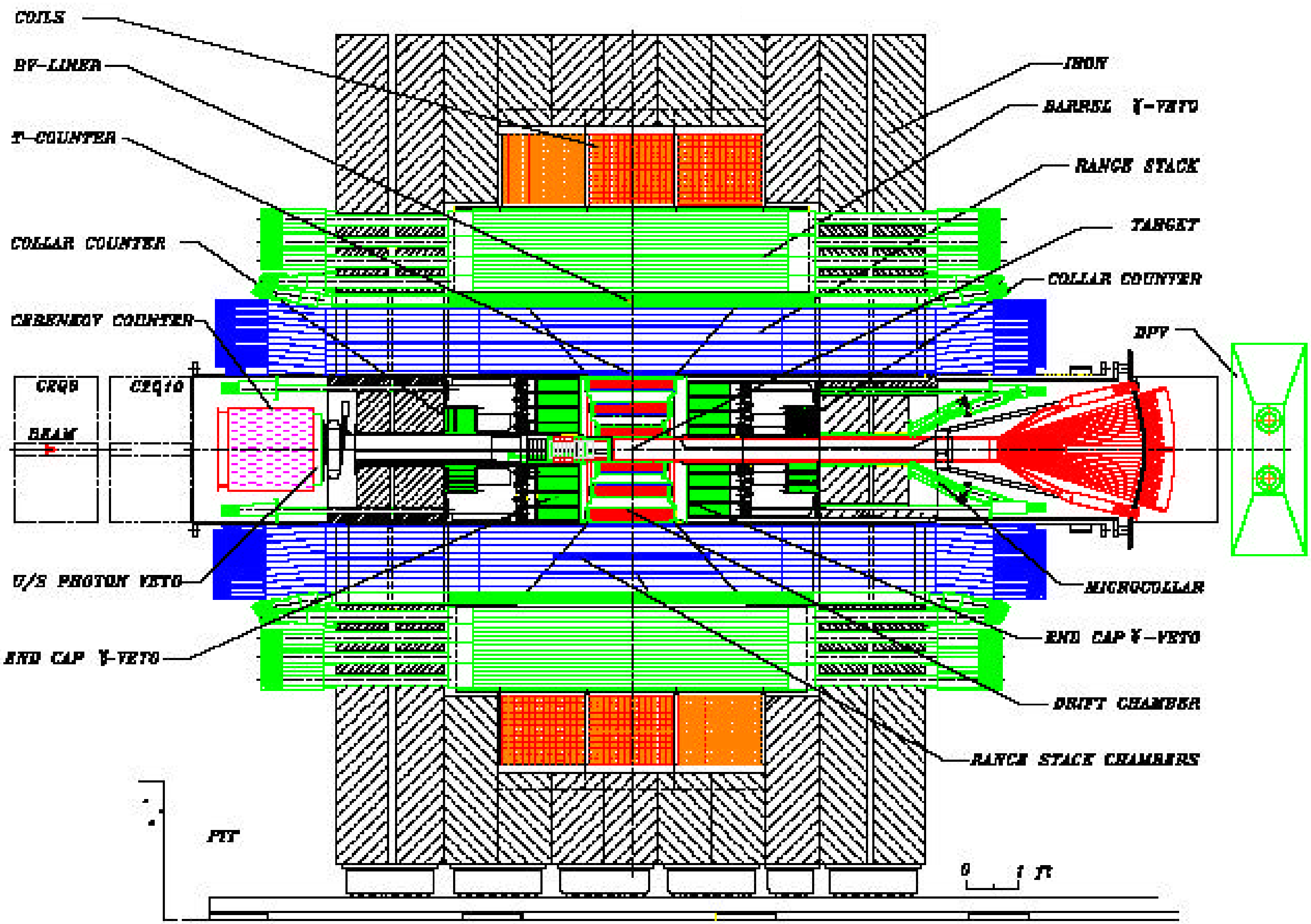


Analysis strategy (3)

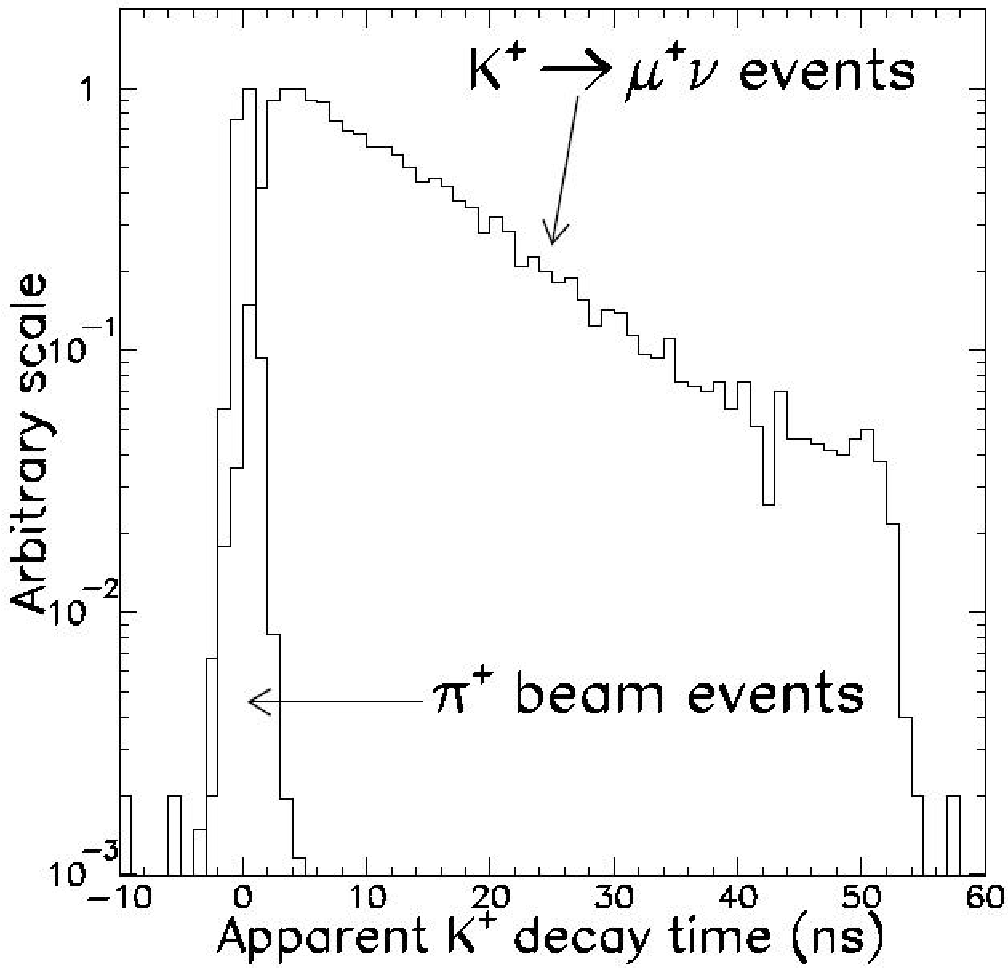
• Verify bg estimates & check for correlations by *simultaneously* loosening both cuts and comparing observed and predicted number of events remaining. Construct background functions by varying *one cut at a time*, keeping the other inverted.



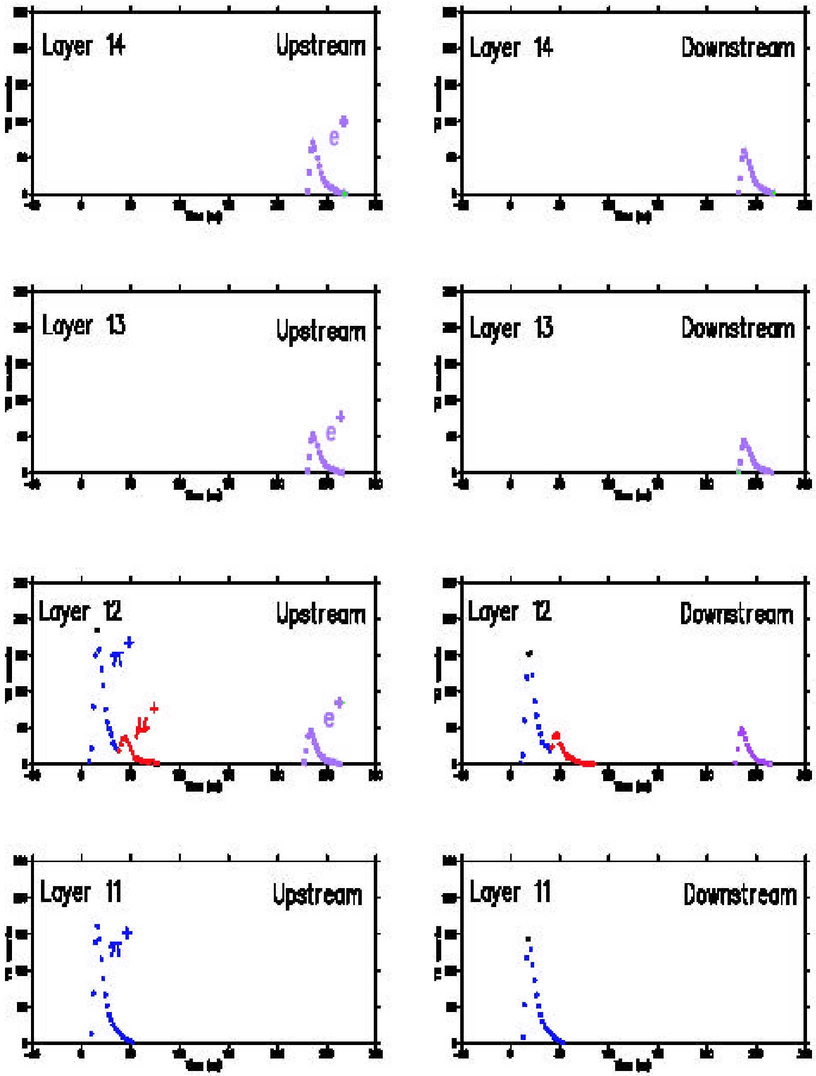
The E949 detector



Delayed coincidence



ð$^+$ ® ì$^+$ ® e$^+$ identification

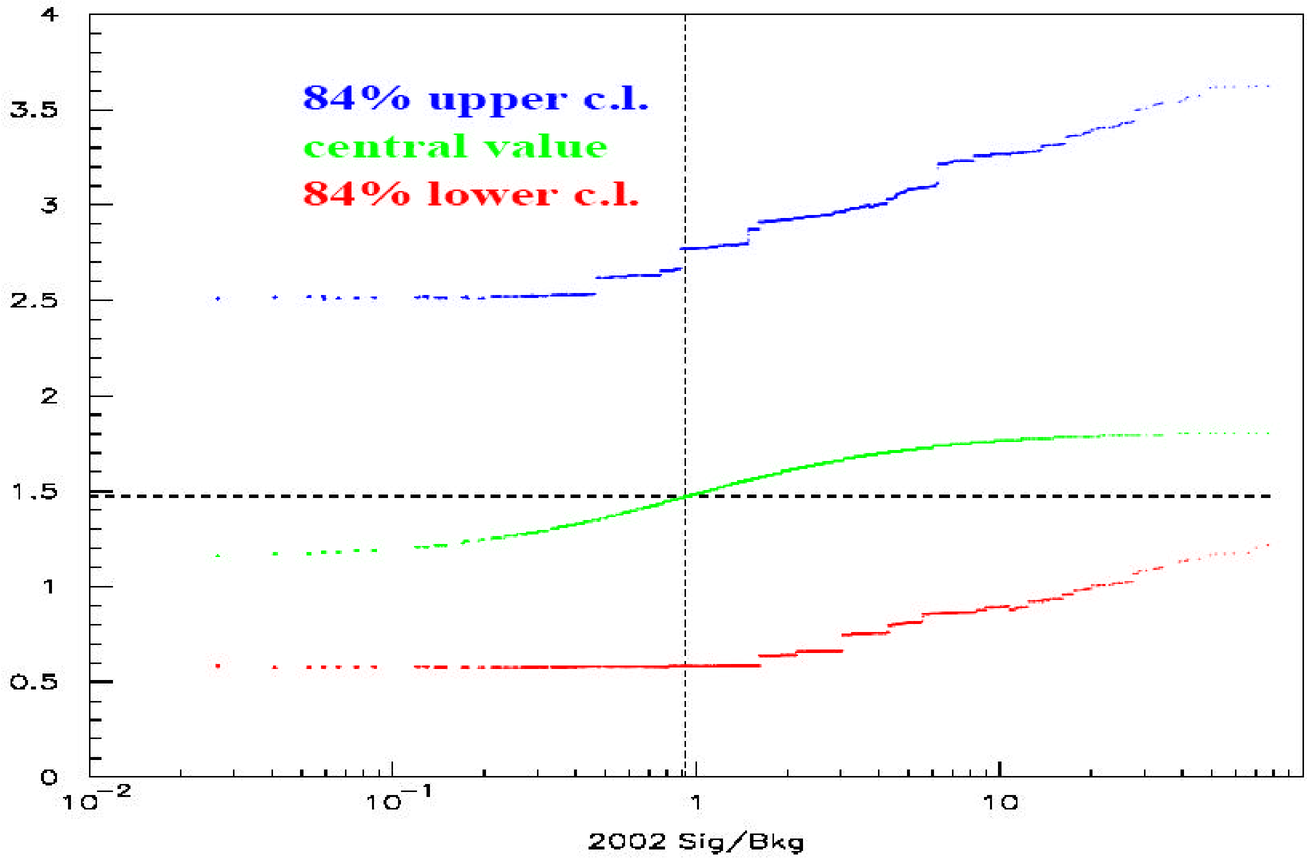


$E_{ì}$ = 4.1 MeV, $R_{ì}$ ~ 1 mm,
$ô_{ð}$ =26 ns

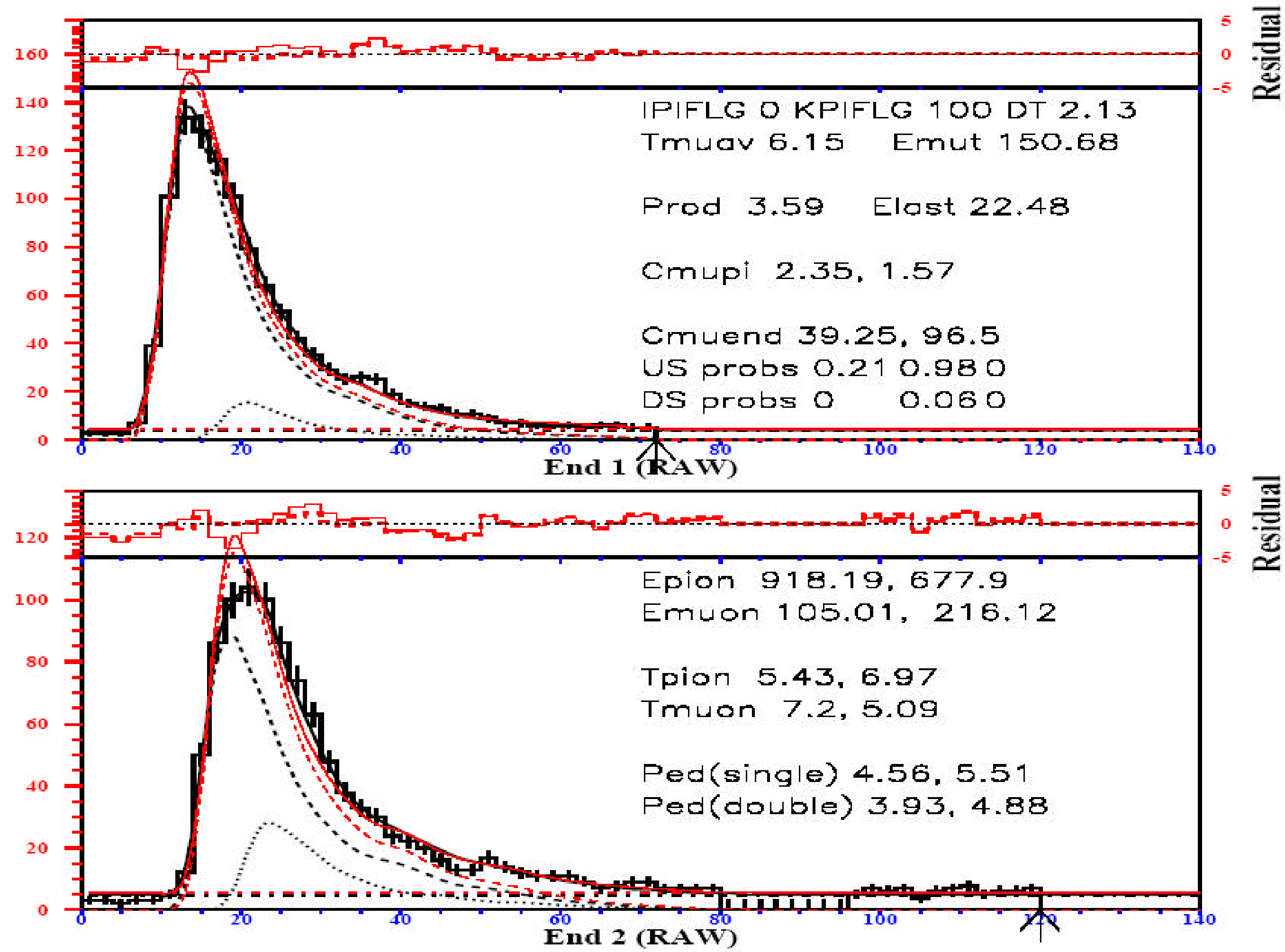
E_e < 53 MeV, $ô_{ì}$ = 2.2 ìs

Toy MC for Junk code

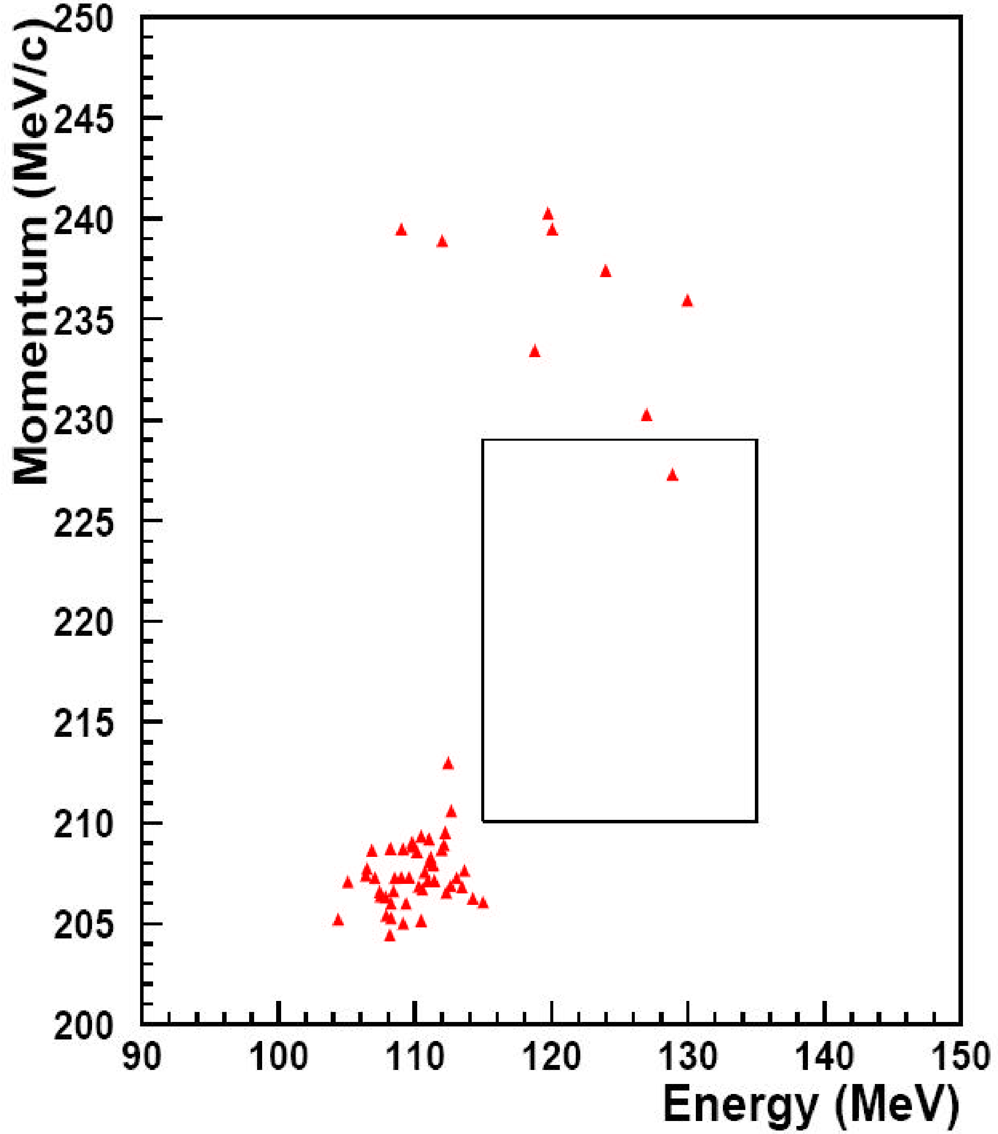
BR dependence on s/b of cell where event is found:



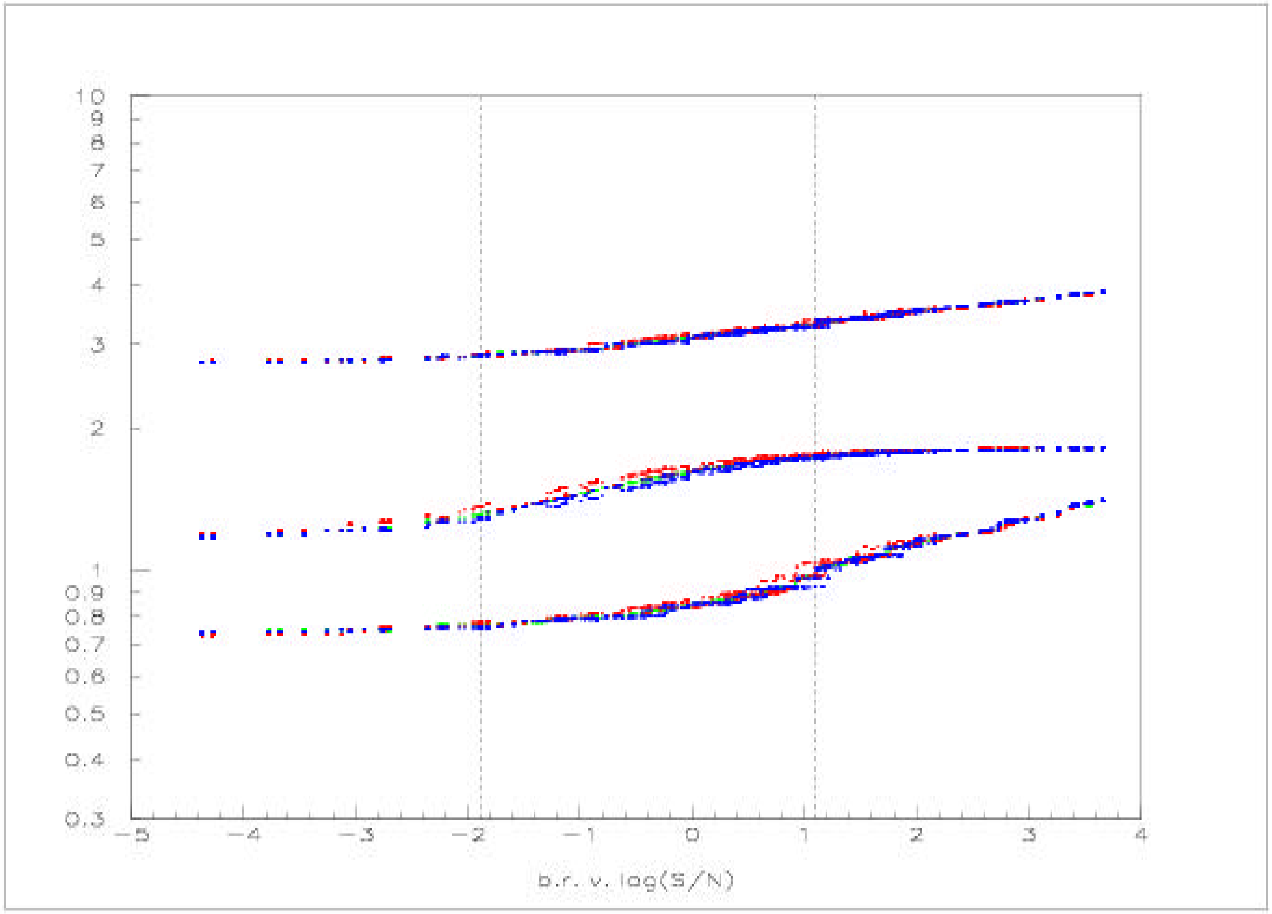
Pulse fitting in stopping counter



Another view of the event



Effect of systematics on BR



Combined (E787 & E949) 84% upper and lower limits and central value of BR for single simulated events in the 2002 data set, with variations of the assumed Kp2 bg component of ±30%